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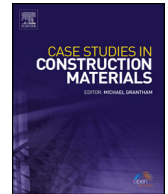
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Critical analysis of strength estimates from maturity functions

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ABSTRACT

Strength estimates from the following maturity functions: Nurse-Saul, Rastrup, Weaver and Sadgrove, Freiesleben Hansen and Pedersen, and the Dutch Weighted Maturity have been compared with actual strengths of concretes cured with temperature histories of *in-situ* blocks, adiabatic and isothermal 50 °C curing. Three concrete mixes with a 28-day nominal cube compressive strength of 50 MPa have been investigated in this work. The first was a neat Portland cement mix whilst the other included partial cement replacement with fly ash (FA) and ground granulated blast furnace slag (GGBS) at 30 and 50% cement replacement levels respectively. High early age temperatures, such as those occurring in adiabatic or isothermal tests, appear to affect adversely the strength estimates and this is believed to be due to the detrimental effect of high curing temperatures on strength starting from a very early age. None of the maturity functions accounts for the detrimental effect of high curing temperatures on later age strength and thus all of them overestimate the later age strengths. It is believed that consideration of this detrimental effect in the maturity functions will improve the strength estimates for both early and later ages.

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1. Introduction

The need for estimating the effects of steam treatments on strength development led, in around 1950, to the development of maturity methods which aimed at accounting for the combined effect of time and temperature on the strength development. An outgrowth of studies followed which dealt not only with accelerated curing but also with (a) estimation of in-place strength based on strength development data obtained under standard laboratory conditions [1–7] and (b) later age prediction based on early age strengths [8–10].

The interest in estimation of in-place strengths was the result of failures during construction blamed on premature removal of formwork. Two notable failures were: (a) the Skyline Plaza apartment building at Bailey's Crossroads in Fairfax County, Virginia, which collapsed in March 1973 killing 14 workers and injuring 35 others [11], and (b) the Willow Island, West Virginia, cooling tower collapse in 1978 which killed fifty-six [12,13]. The benefits arising from accelerated construction schedules, e.g. faster formwork striking times resulting from real-time compressive strength monitoring, have led to the development and commercialisation of maturity meters [14–23]; from simple handheld ones to even wireless sensors transmitting information to smartphones.

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Numerous maturity functions [6,24–35] have been proposed and the ones that have gained popularity in the UK, USA and Netherlands [25,34,36–42] are briefly reviewed/described in the next section. Three concrete mixes with a 28-day nominal cube compressive strength of 50 MPa have been investigated in this work. The first was a neat Portland cement mix whilst the other included partial cement replacement with fly ash (FA) and ground granulated blast furnace slag (GGBS) at 30 and 50% cement replacement levels respectively. Strength estimates of these mixes cured under *in-situ*, adiabatic and isothermal (50 °C) conditions were determined and compared to actual values from cubes cured in the laboratory replicating these curing conditions. The accuracy of these estimates was the main focus of this work.

2. Maturity functions

The following maturity functions:

- (a) Nurse-Saul [24,43],
- (b) Rastrup [26],
- (c) Weaver and Sadgrove [6]
- (d) Freiesleben Hansen and Pedersen [35],
- and,
- (e) The Dutch Weighted Maturity [44–46],

are briefly reviewed/described below. Common to all of these is the need for a relationship between compressive strength and time/age or maturity index [25]. The Three Parameter Equation (TPE) has been suggested by Freiesleben Hansen and Pedersen (FHP) and is as follows [47]:

$$S = S_u e^{-(\frac{t}{\tau})^\alpha} \quad (1)$$

where: S is compressive strength at age t (MPa),
 S_u is the ultimate compressive strength (MPa),
 τ is the characteristic time constant (days),
 t is the test age (days),
 α is a shape parameter.

2.1. The Nurse-Saul function

Saul [24] introduced the maturity concept/index, in 1951, which is a single factor, proposing that at the same maturity, for a given concrete mix, corresponds to the same strength regardless of the combination of temperature and time that make up that maturity:

$$M = \sum (T - T_0) \Delta t \quad (2)$$

where: M is the maturity (°C-days),
 T is the average temperature (20 °C for standard curing) over the time interval Δt (°C),
 T_0 is the datum temperature (°C),
 Δt is the time interval (days).

The datum temperature corresponds to the temperature below which it is assumed that no strength gain occurs. In this work, the datum temperature was chosen to be equal to −11 °C, which is the average of what is recommended in the literature [34,48,49]. The above equation has become known as the Nurse-Saul function and assumes that the rate of strength development is a linear function of temperature. It can be used to convert a given temperature-time curing history to an equivalent age of curing at a reference temperature as follows:

$$t_e = \frac{\sum (T - T_0)}{(T_r - T_0)} \times \Delta t \quad (3)$$

where: t_e is the equivalent age at the reference temperature (days),
 T_r is the reference temperature (°C).

Equivalent age represents the duration of the curing period at the reference temperature that would result in the same maturity as the curing period at other temperatures. Eq. (3) can be written as follows [25]:

$$t_e = \sum \beta \times \Delta t \quad (4)$$

and the age conversion factor, β , is:

$$\beta = \frac{(T - T_0)}{(T_r - T_0)} \times \Delta t \quad (5)$$

where: T_r is the reference temperature ($^{\circ}\text{C}$),

T is the average temperature (20°C for standard curing) over the time interval Δt ($^{\circ}\text{C}$),

T_0 is the datum temperature ($^{\circ}\text{C}$),

β is the age conversion factor.

The ratio β , which is called the “age conversion factor”, has a simple interpretation: it converts a curing interval Δt to the equivalent curing interval at the reference temperature [25].

The above rely on Saul's maturity principle that has become known as the “maturity rule”, being valid, i.e.: “Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity”. However, Saul noted that this principle was only valid provided the concrete temperature did not exceed 50°C within the first 2 h or about 100°C within the first 6 h after the start of mixing. Later studies [50,51] also confirmed that at the same value of low maturity, a high curing temperature results in greater strength than a low curing temperature, and conversely at later maturities, result in lower strength. This “crossover effect” was presented in 1968 [52]. It was suggested that a higher initial temperature results in more than a proportional increase in the initial rate of hydration. Therefore, during the early stage of curing, when there is rapid strength development, the strength of concrete cured at the high temperature is greater than that of concrete cured at a lower temperature despite having the same maturity.

2.2. The Rastrup function

The equivalent age concept is a convenient method for using other functions besides Eq. (2) to account for the combined effect of time and temperature on strength development. It was originally suggested by Rastrup [26] based on an axiom from physical chemistry, which stated that the rate of reaction is double if the temperature at which the reaction is occurring is increased by 10°C :

$$t_e = \sum 2^{(T-T_r)/10} \Delta t \quad (6)$$

where: t_e is the equivalent age at the reference temperature (days),

T_r is the reference temperature ($^{\circ}\text{C}$).

In this case, the age conversion factor is:

$$\beta = \sum 2^{(T-T_r)/10} \Delta t \quad (7)$$

where: t_e is the equivalent age at the reference temperature (days),

T_r is the reference temperature ($^{\circ}\text{C}$).

2.3. The Weaver and Sadgrove function

Another method for calculating the equivalent age was proposed by Weaver and Sadgrove [6] and is expressed as follows:

$$t_e = \sum \left(\frac{T+16}{T_r-16} \right)^2 \times \Delta t \quad (8)$$

where: t_e is the equivalent age at the reference temperature (days),

T_r is the reference temperature ($^{\circ}\text{C}$).

The age conversion factor in the above is:

$$\beta = \left(\frac{T+16}{T_r-16} \right)^2 \quad (9)$$

2.4. The Freiesleben Hansen and Pedersen (Arrhenius) function

Freiesleben Hansen and Pedersen's (FHP) expression for equivalent age is based on the assumption that the rate of strength development obeys the Arrhenius equation and this led to the maturity function (referred to as Arrhenius function in this paper) [35]:

$$t_e = \sum e^{-\frac{E_a}{R} \left(\frac{1}{T_a} - \frac{1}{T_s} \right)} \times \Delta t \quad (10)$$

where: t_e is the equivalent age (days),

T_a is the average temperature of concrete during time interval Δt ($^{\circ}\text{K}$),

T_s is the specified reference temperature ($^{\circ}\text{K}$),

E_a is the apparent activation energy (J/mol),

R is the universal gas constant ($\text{J}/^{\circ}\text{K}\cdot\text{mol}$).

In this case the age conversion factor is:

$$\beta = e^{-\frac{E_a}{R} \left(\frac{1}{T_a} - \frac{1}{T_s} \right)} \quad (11)$$

2.5. The Dutch “Weighted Maturity” function

In 1979, De Vree and Tegelaar [44] proposed a maturity method called “Weighted Maturity” which was based on the study carried out by Papadakis and Bresson [53]:

$$M_w = \sum t \times T \times C^n \quad (12)$$

where:

M_w is the weighted maturity ($^{\circ}\text{C}\cdot\text{h}$ or $^{\circ}\text{C}\cdot\text{days}$)

t is the age/time of concrete (h or days)

T is the average concrete temperature during time interval Δt ($^{\circ}\text{C}$)

n is a temperature dependent parameter

C is a cement specific constant for which the strength maturity curves for isothermal strength tests at 20 and 65°C coincide, C – cement specific value.

Two additional parameters appear to have been introduced in Saul’s maturity index to overcome its deficiencies. These are: (a) the “ C ” value which is cement specific and thus different values can be used depending on the cement strength but also allowing for use of additions (otherwise known as supplementary cementitious materials), and, (b) the “ n ” value which allows for a non-linear effect of temperature on the strength development. This is temperature dependent and may be calculated from the following equation:

$$n = 0.1 \times T - 1.245 \quad (13)$$

The “ C ” and “ n ” values combined as C^n make up the “weighted factor” which, for values of C greater than one, increases almost exponentially with temperatures above 12.45°C . Some values for “ C ” have been provided [45,46], i.e. $C = 1.25$ for CEM I 32.5R, 52.5, 52.5R and CEM II/B-V 32.5R, $C = 1.65$ for CEM III/B 42.5 LH HS, $C = 1.60$ for CEM II/B 42.5 LH HS plus, and $C = 1.0$ for CEM III/A 52.5 and CEM V/A 42.5. Values can also be determined by casting ten 150 mm concrete or 40 mm mortar cubes (both with water to cement ratio of 0.5) and determining their strength development at 20°C and 65°C . A value of C is then determined by trial and error so that the compressive strengths plotted against weighted maturity overlap.

The weighted maturity can be expressed as follows [34]:

$$M_w = \sum \Delta M_w \times t \quad (14)$$

where

$$\Delta M_w = \Delta t \cdot \int_{-10}^T C^{0.1T-1.245} \times dT \quad (15)$$

or

$$\Delta M_w = \frac{10(C^{0.1T-1.245} - C^{-2.245})}{\ln C} \quad (16)$$

It follows from the above that the age conversion factor is:

$$\beta = \frac{C^{0.1T-1.245} - C^{0.1T_r-2.245}}{C^{0.1T_r-1.245} - C^{0.1T-2.245}} \quad (17)$$

3. Research significance

The maturity functions described above have been used in several commercially available maturity meters. However, the accuracy of their strength estimates is rarely, if at all, investigated. There are difficulties in doing this. The best method would be to use a temperature matched curing tank adjacent to the structure. There are, however, logistics to consider such as transportation of concrete cubes to a testing laboratory. The aim of this work was, therefore, not only to compare the accuracy of strength estimates of the five maturity functions described above but to also identify the reasons for any inaccuracies that may arise due to: (a) early age temperature rise such as that occurring in adiabatic or isothermal tests and (b) the use of additions (also known as supplementary cementitious materials). Both of these have become important factors to consider especially in precast concrete works. The new types of cements (CEM II – Portland composite cement, CEM III – blast furnace slag cement, CEM IV – pozzolanic cement and CEM V – composite cement) are gaining popularity because of their lower than CEM I – Portland cement carbon footprint. Cements containing additions are also required in several

exposure conditions, such as XD3, XC3 and XS3 [54]. These cements develop strength slower and may cause problems for precast concrete factories where the early age strength requirement, e.g., 15 MPa for reinforced and 24 MPa for prestressed concretes at 16 h, may be difficult to achieve without high early age curing temperatures applied immediately after casting, i. e. not have the “delay period” before the “temperature rise period” as is normally recommended for precasting works [55].

4. Materials and experimental procedures

The concrete mixes in this work were those used in the Department of Trade and Industry (DTI) concrete core project [56]. These had a 28-day nominal cube compressive strength of 50 MPa and included partial cement replacement with fly ash (FA) and ground granulated blast furnace slag (GGBS) at 30 and 50% cement replacement levels respectively. The mixes were replicated in the laboratory and they have previously been reported in [57]. The mix proportions of the concretes and their equivalent mortars are shown in Table 1.

4.1. Materials

Portland cement (PC), conforming to requirements of BS EN 197-1:2011 [58] and having a 28-day compressive strength of 57 MPa (tested according to BS EN 196-1-2005 [59]), was supplied in bags by British Lime Industries. PC was partially replaced with GGBS and FA conforming to BS EN 15167-1:2006 [60] and BS EN 450-1:2012 [61] respectively. GGBS was supplied in bags by the Appleby Group whereas FA was supplied in sealed plastic buckets by Fiddlers Ferry, a coal-fired electricity-generating station, in Warrington, UK. The chemical composition of PC, GGBS and FA are shown in Table 2.

The coarse aggregate used was 5–20 mm uncrushed round gravel from the Fagl Lane quarry, which is located in Wales. Its specific gravity and water absorption were 2.64 and 1.7%, respectively. The fine aggregate used was well graded fine aggregate obtained also from the Fagl Lane quarry having specific gravity of 2.60 and water absorption of 2.6%. The grading curves for the gravel and sand are shown in Fig. 1, as are also shown the overall grading limits from BS882:1992 [62] which has since been replaced with BS EN 12620:2002+A1:2008 [63].

4.2. Mixing, casting, curing and testing procedures

All concrete mixes were batched using a 0.1 m³ capacity horizontal pan mixer. Binder and aggregate were placed first in the mixing pan and dry-mixed for one minute. Water was then added and mixing continued for a further five minutes. The consistency

Table 1

Concrete mixes and their equivalent mortars.

Mix ID	PC		50GGBS		30 FA	
	Concrete	Equivalent mortar	Concrete	Equivalent mortar	Concrete	Equivalent mortar
PC [kg/m ³]	345	442	165	219	270	332
GGBS [kg/m ³]	–	–	165	219	–	–
FA [kg/m ³]	–	–	–	–	115	141
Gravel [kg/m ³]	1205	–	1151	–	1250	–
Sand [kg/m ³]	615	1519	683	1588	533	1523
Free water [kg/m ³]	160	204	165	200	135	166
Free w/b [–]	0.46	0.46	0.50	0.46	0.35	0.35
Concrete slump [mm]	135	–	120	–	10	–

Table 2

Chemical composition of PC, GGBS and FA.

Chemical composition (% by weight)			
Chemical constituent	PC	GGBS	FA
SiO ₂	20.11	35.35	48
Al ₂ O ₃	5.16	14	27
Fe ₂ O ₃	3.14	0.36	9
CaO	65.49	41.41	3.3
MgO	0.8	7.45	2
SO ₃	3.22	0.1	0.6
K ₂ O	0.59	–	3.8
Na ₂ O	0.13	–	1.2
CaCO ₃	4.47	–	–
Equiv. Alks Na ₂ Oe	0.52	–	–
Free Lime	1.79	–	–
Chloride	71 ppm	–	–
LOI	2.8	0.31	4.9

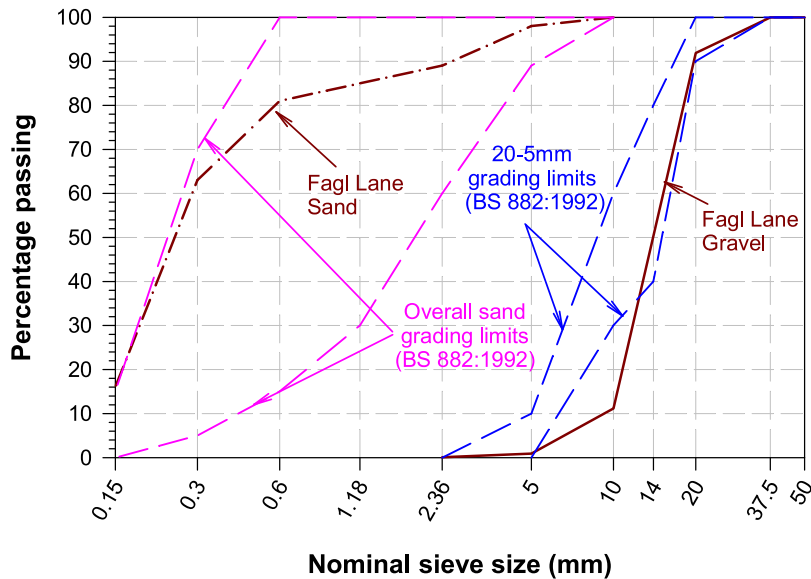


Fig. 1. Sieve analysis of coarse and fine aggregate.

was assessed by carrying out the slump test according to BS EN 12350-2:2009 [64]. All equivalent mortar mixes were cast in one batch using a 0.02 m³ capacity horizontal pan mixer. The materials were mixed dry for one minute, then water was added and mixing continued for a further three minutes. Concrete cube specimens (100 mm size) or mortar cube specimens (50 mm size) were subsequently cast in two layers in single- and three-gang steel moulds, and each layer was compacted using a vibrating table.

Several different curing procedures were used and these are described below:

- **Isothermal and standard curing** for which the concrete specimens, inside single cube moulds, were covered with wet hessian and a polythene sheet immediately after casting and left to cure at room temperature conditions (approximately 20 °C) [65] for a day. They were subsequently demoulded and placed inside a water bath set at 20 °C. In the case of mortars, after consolidation of the cubes, the moulds were wrapped in polyethylene film to ensure they were sealed in order to avoid wash out when they were transferred to water tanks for curing at 20, 30, 40 and 50 °C. For curing at 10 °C, the specimens were wrapped in damp hessian and stored in an incubator. They were demoulded at the time of the first compressive strength test. Three cubes were tested at six to eight testing ages for each mix/temperature combination. In each case, the first testing age corresponded to a compressive strength of approximately 4 MPa, achieved by trial and error, and subsequent tests were carried out at twice the age of the previous test.
- **Temperature matched curing (TMC), i.e. replicated *in-situ* temperature histories** for which the concrete specimens, inside three-gang moulds, were sealed using a cling film and a tape and placed inside programmable computer controlled water tanks. They were cured under TMC conditions using temperature histories recorded during the DTI project [56,57]. The programmable computer controlled water tank shown in Fig. 2 was used to simulate the *in-situ* temperature histories. The cling film was removed at 24 h after casting, but the cubes were placed back in the tank until they were tested.
- **Adiabatic curing** - The adiabatic temperature rise due to hydration of cement will occur if there are no heat losses from the fresh concrete. To achieve this state, it is necessary to either heavily insulate the concrete or alternatively to ensure that the environment in which the concrete is stored is at the same, or nearly the same, temperature as the concrete. The latter approach was adopted in this study. Concrete (150 mm cube) was cast in a steel box lined with 20 mm expanded polystyrene for insulation and heavy-duty polyethylene to prevent moisture loss. The specimen was then placed into a programmable computer controlled curing tank and two copper/constantan thermocouples were inserted in it through a hole in the top of the box. Two more copper/constantan thermocouples were used to monitor the temperature of the water in the tank. The thermocouples were all connected to a computer which not only recorded the temperatures but also was set to activate the water heating system when the temperature difference between the water and the concrete was >1 °C. It can be assumed, based on the fact that there was no temperature drop after the maximum had been reached, that there was only very little heat loss and thus no adjustment was needed for the results. A schematic diagram of the setup of the programmable computer controlled curing tank used for adiabatic tests is shown in Fig. 2. In addition, concrete specimens, inside three gang-moulds, were sealed using a cling film and tape and placed inside the programmable computer controlled curing tank so that the compressive strength could be determined for the adiabatically curing regime [66].

The testing ages for the standard cured concrete specimens were 1, 2, 3, 5, 7, 14, 28, 42, 84, 156 and 365 days, while TMC and adiabatically cured concrete specimens were tested at 1, 2, 3, 5, 7, 14 and 28 days. The testing ages for the mortar

specimens were 0.5, 1, 2, 4, 8, 16, 32, 64 and 128 days. At each testing age 3 specimens from each curing regime were tested in order to determine an average compressive strength.

5. Results and discussion

The strength development of concretes and their equivalent mortars is presented first followed by the determination of apparent activation energies and of the weighted factor C^n which are both needed for making possible a comparison between the age conversion factors inherent in each maturity function. Strength estimates from the five maturity functions and for the PC, 50GGBS and 30 FA mixes cured under (a) *in-situ*, (b) adiabatic and (c) isothermal (50 °C) conditions are then compared to actual compressive strength values obtained from cubes cured in the laboratory replicating these curing conditions.

5.1. Strength development of concretes and their equivalent mortars

The strength development curves for the three mixes, i.e. PC, 50GGBS and 30 FA are shown in Fig. 3 whilst the TPE (Eq. (1)) was used for the regression curves. It does appear that 30 FA concretes had 28-day compressive strengths that were higher than those of the corresponding PC and 50GGBS mixes. The figure also shows FA's long-term contribution to compressive strength development. The early age compressive strength of GGBS mix is shown to be lower than the equivalent ones of PC and even FA mixes. Fig. 4 shows the compressive strength development of the equivalent mortar mixes. Although similar some differences are noted, e.g., a more pronounced S shape curve for PC, slightly higher early age strengths in 30 FA, and the 50GGBS achieving higher strengths than 30 FA at 365-days. The Three Parameter Equation (TPE) that has been suggested by Freiesleben Hansen and Pedersen (FHP), i.e. Eq. (1), has been used for determining the strength versus time relationship. The constants are shown in Table 3 as these are needed to estimate strengths once the equivalent age has been determined with the use of the above described maturity functions.

5.2. Age conversion factors

A good way of showing how the maturity functions deal with the effect of temperature on the strength gain rate for different types of concretes is by comparing their age conversion factors that have been discussed above. The age conversion factor is how the maturity functions convert a curing interval Δt into the equivalent curing interval at the reference temperature [25].

The age conversion factors in the Nurse-Saul, Weaver-Sadgrove and Rastrup functions are independent of the mix. It is only the Arrhenius and the Dutch weighted maturity methods that are mix specific. The former requires the determination of apparent activation energies whilst the latter requires the weighted factor C^n . These will first be determined so that the age conversion factors in all the maturity functions are subsequently compared.

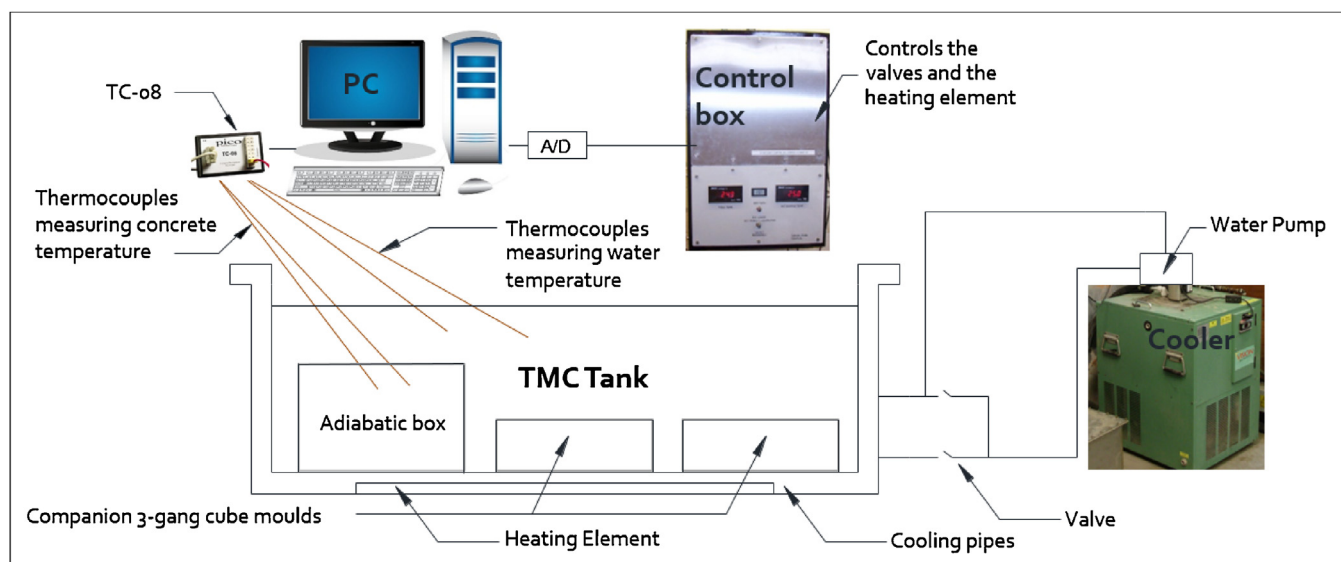


Fig. 2. Schematic diagram of the computer controlled TMC tank setup for the adiabatic tests.

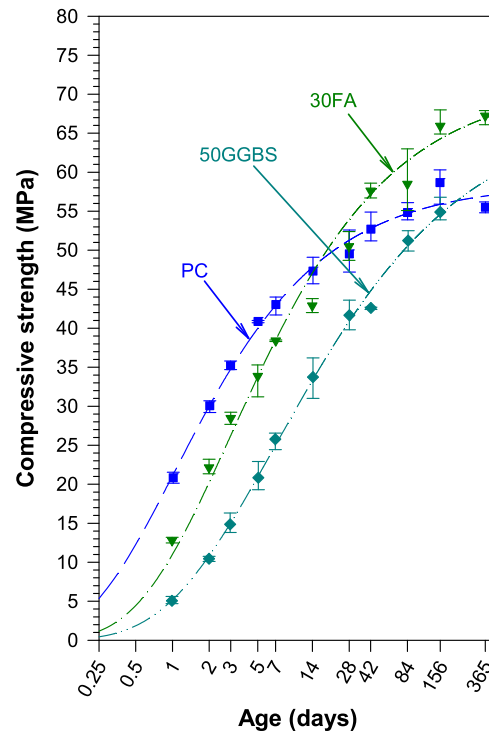


Fig. 3. Concrete compressive strength development regression plots using Eq. (1).

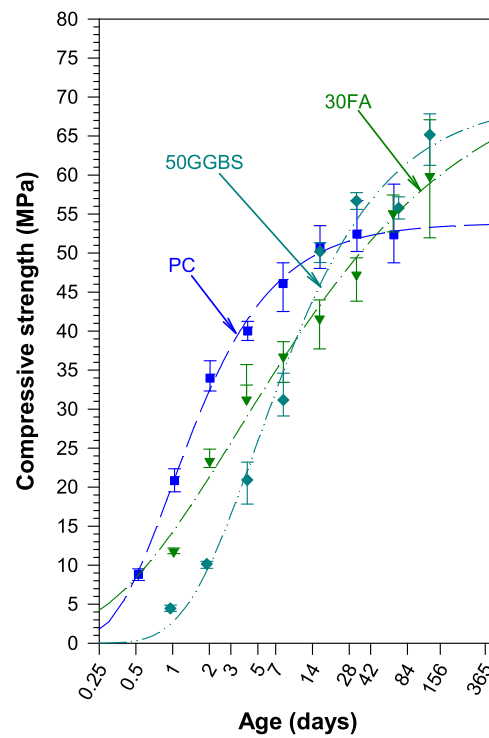


Fig. 4. Mortar compressive strength development regression plots using Eq. (1).

Table 3
Regression parameters for strength-time relationship.

FHP-TPE (Eq. (1))									
Mix ID	PC			50GGBS			30 FA		
Regression parameters	S_u [MPa]	τ [days]	a	S_u [MPa]	τ [days]	a	S_u [MPa]	τ [days]	a
Concrete									
Standard curing [20 °C]	58.6	1.03	0.61	66.2	6.57	0.50	76.8	3.30	0.44
Mortar									
Standard curing [20 °C]	53.8	0.97	0.93	69.6	4.92	0.74	74.8	3.54	0.40

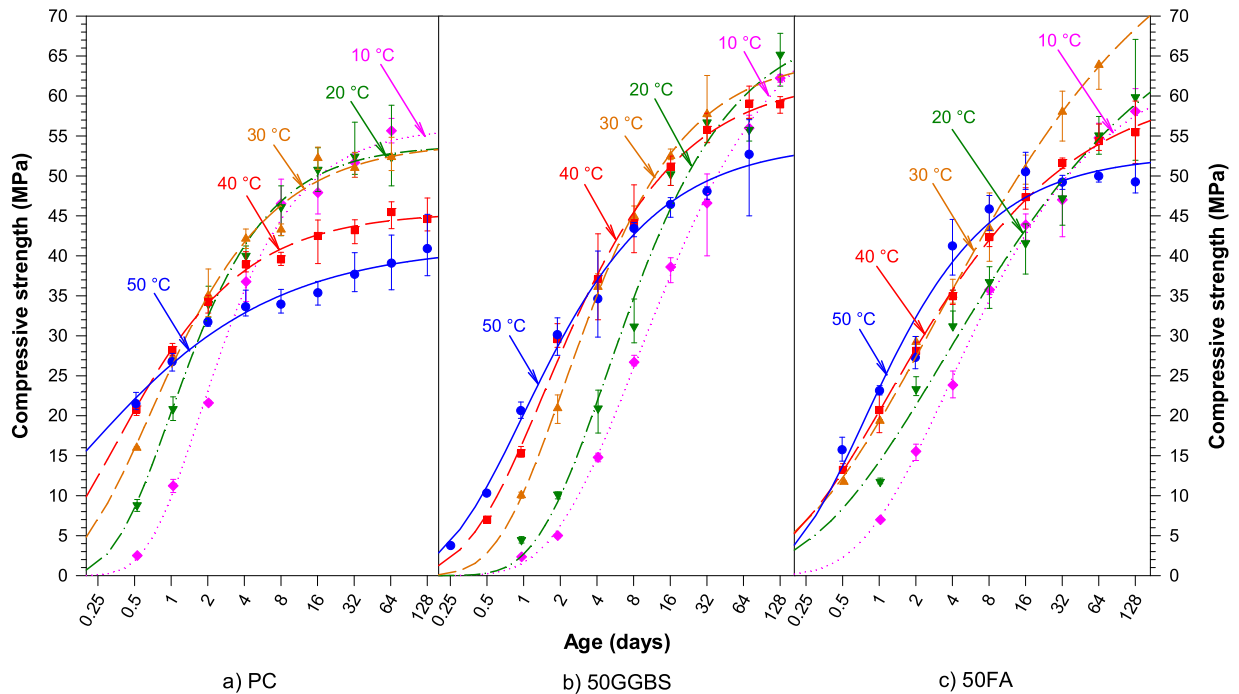


Fig. 5. Mortar compressive strength development regression plots using Eq. (1).

Table 4
Regression parameters for mortar strength-time relationship.

FHP-TPE (Eq. (1))										
Mix ID	PC			50GGBS			30 FA			
Regression parameters	S_u [MPa]	τ [days]	a	S_u [MPa]	τ [days]	a	S_u [MPa]	τ [days]	a	
Curing	10	56.1	1.77	0.97	74.1	8.61	0.62	64.9	3.75	0.6
Temperature [°C]	20	53.8	0.97	0.93	69.6	4.92	0.74	74.8	3.54	0.40
	30	54.3	0.66	0.74	65.1	2.17	0.78	86.8	2.93	0.38
	40	45.5	0.36	0.72	62.4	1.48	0.68	61.9	1.22	0.50
	50	41.4	0.19	0.48	59.2	0.98	0.68	52.7	0.75	0.73
Ea [kJ/mol]		41.2			42.3			32.1		

5.2.1. Determination of apparent activation energies

The determination of the apparent activation energy is necessary as it is required for the Arrhenius method. According to ASTM C1074-11 [67], “equivalent” mortar mixes can be used to determine the activation energy of concrete mixes. The compressive strength development with age at different curing temperatures is shown in Fig. 5. As expected, the strength development of all the mortars depended on the curing temperature. At early ages, the strength was higher at higher temperatures since the rate of reaction was greater. At later ages, the strength was lower at high curing temperatures. This is

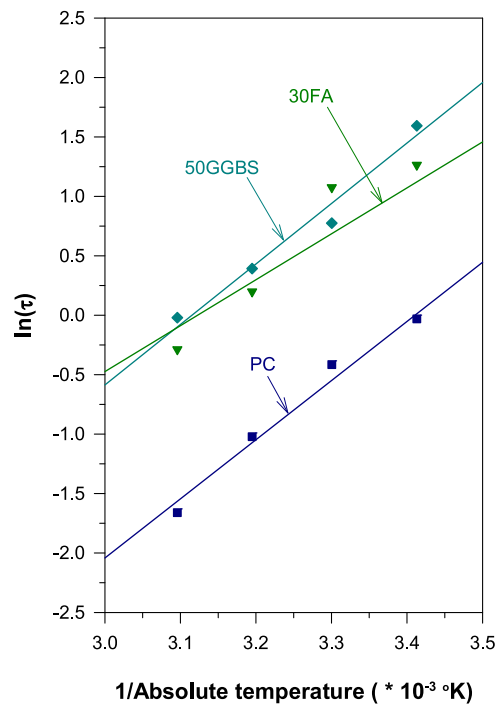


Fig. 6. $\ln(k)$ and $\ln(\tau)$ against absolute temperature.

believed to be due to the formation of dense hydrated phases around the unreacted cement particles, preventing further hydration [68–70]. The non-uniform distribution of hydration products also leads to larger pores in the microstructure. The mortars containing GGBS were more sensitive to temperature, with their early-age strengths showing a wider variation with temperature. This clearly shows the benefit of higher curing temperatures on the early-age strength development of mortars, especially those containing GGBS. Regression lines are based on the TPE, i.e. Eq. (1), and the regression constants determined are shown in Table 4.

The procedure for calculating the apparent activation energy, E_a , is to plot the natural logarithm of the characteristic time constant (see τ in Eq. (1) and Table 4), i.e. $\ln(\tau)$, against $1/T_{abs}$ (given in 1/Kelvin) and this is shown in Fig. 6. The apparent activation energies determined were 41.2 kJ/mol for PC, 42.3 kJ/mol for 50GGBS and 32.1 kJ/mol for 30 FA.

The apparent activation energy for GGBS is much higher than FA concrete which confirms that GGBS concrete is more temperature sensitive. The apparent activation energy for neat PC concrete was unexpectedly similar to GGBS but this appears to be because of the determination method used, i.e. the TPE strength-time relationship was used for regression analysis rather than the ASTM C1074-11 recommended one [67,71,72]. The difference in the apparent activation energies determined on the same set of data is quite high; 41.2 kJ/mol by using the TPE compared to only 29.7 kJ/mol by using the ASTM C1074-11 recommended one [65]. The apparent activation energies for the other mixes determined using the regression equation of ASTM C1074-11, and which have been reported elsewhere [65], were 41.6 kJ/mol for 50GGBS and 27.3 kJ/mol for 30 FA and thus they were similar to those determined with the TPE.

5.2.2. Determination of weighted factor C^n

The Dutch “weighted maturity” method requires the weighted factor C^n instead of the “apparent” activation energy. The NEN 5970 [46] standard’s recommendation for determining this factor is to cast 150 mm concrete cubes or 40 × 40 160 mm mortar prisms and cure a minimum of 5 at 20 °C ± 2 °C and cure another set of five at 65 °C ± 3 °C. The strength results are then plotted against the logarithm of weighted maturity with an assumed C . Trial and error is required to determine a value of C such that the strength data at 20 and 65 °C overlap. This is shown in Fig. 7. It must be noted that the data plotted are however for 50 mm mortar cubes and these were cured at 20 and 50 °C instead of 20 and 65 °C. It appears that the Dutch weighted maturity method acknowledges the existence of the cross-over effect and thus only requires compressive strengths plotted up to 35 MPa for cement of strength class 42.5 (R) and 52.5 (R). Despite excluding later age strengths the cross-over effect for the PC is apparent in Fig. 7 and a good overlap between the 20 and 50 °C strength data could not be obtained; the relationships for the two temperatures had different gradients.

The values for the weighted maturity C were determined to be 1.17, 1.44 and 1.04 for neat PC, 50GGBS and 30 FA, respectively. As expected the 50GGBS had the highest weighted maturity C indicating again that the GGBS concrete is more temperature sensitive. De Vree and Tegelaar [44] recommended values for the weight factor C of (a) 1.25 for CEM I, (b) 1.25

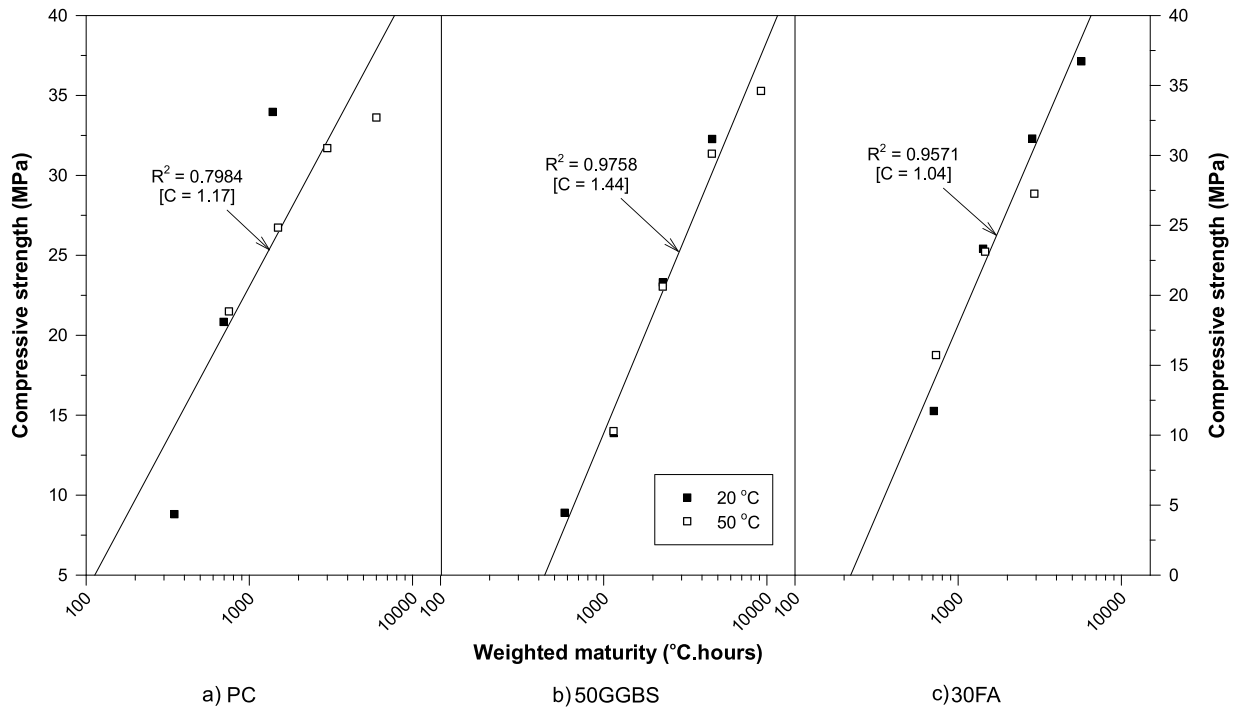


Fig. 7. Best fit regression line for the determination of C value for weighted maturity.

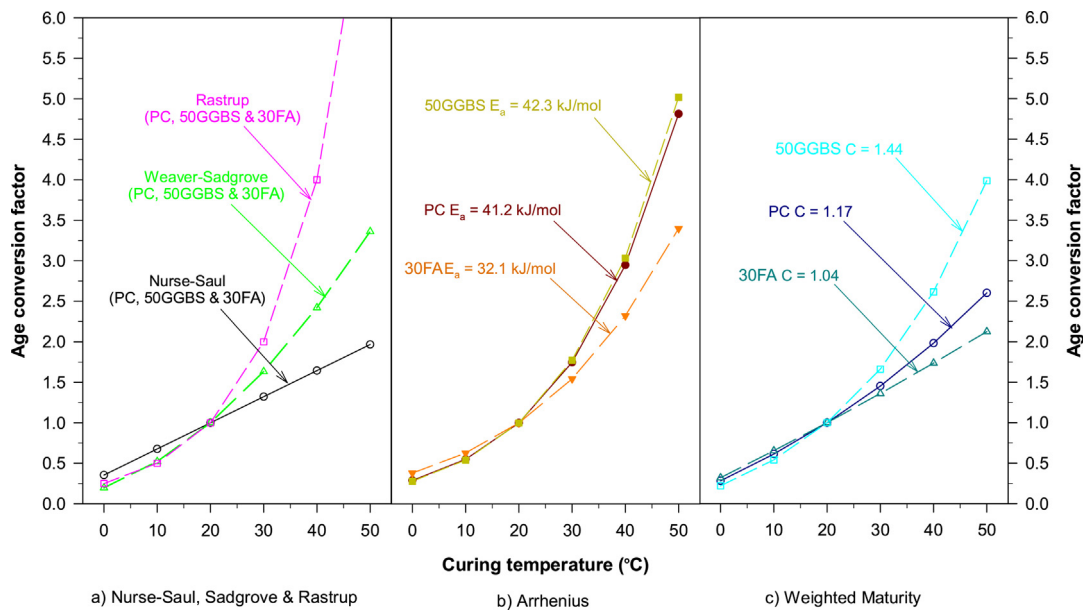


Fig. 8. The effect of temperature on the age conversion factors inherent in investigated maturity functions for various concretes/mortars.

for CEM II/B-V [73], i.e. 21–35% FA, 1.40 for CEM III/A [73], i.e. 46–65% GGBS. Slightly lower values than these have been obtained for the PC and 30 FA mixes but the value for 50GGBS is similar.

5.2.3. Comparison of age conversion factors

The age conversion factors are, as already mentioned above, how the maturity functions convert a curing interval Δt into the equivalent curing interval at the reference temperature. How the maturity functions deal with the effect of temperature on the strength gain rate becomes apparent when the age conversion factor is plotted against curing temperature, as shown in Fig. 8. The age conversion factors for different curing temperatures were calculated from Eqs. (5), (7), (9), (11) and (17) for the Nurse-Saul [1], Rastrup [26], Weaver and Sadgrove [6], Freiesleben Hansen and Pedersen [35], and, The Dutch Weighted Maturity methods [44–46], respectively. The reference temperature was taken to be 20 °C. The age conversion factors in the Nurse-Saul, Weaver-Sadgrove and Rastrup functions are independent of the mix and they are thus all three shown in Fig. 8(a). The linear relationship for the age conversion factor with temperature assumed by the Nurse-Saul function is quite different from the other maturity methods that have an exponential relationship. The linear relationship of the Nurse-Saul function is inadequate and it also does not differentiate the temperature sensitivities of the different cementitious systems, particularly for the GGBS mixes which are shown to have an apparent activation energy of 42.3 kJ/mol, see Fig. 8(b) and a C value of 1.44, see Fig. 8(c). The deviation from the linear relationship of the age conversion factor with temperature is thus greatest for GGBS although Fig. 8(b) also shows this to be the case for PC. However, as noted before the activation of 41.2 kJ/mol is higher than the 29.7 kJ/mol determined with the same set of data but with the ASTM C1074-11 recommended strength-time relationship. How these age conversion factors affect the strength estimates of the several maturity functions investigated is discussed next.

5.3. Comparison of strength estimates

The “apparent” activation energies and the weighted factor C' are needed for strength estimates by the Arrhenius and Dutch weighted maturity methods. The Nurse-Saul, Weaver-Sadgrove and Rastrup functions are independent of the mix. All required values are now available for strength estimates of the PC, 50GGBS and 30 FA mixes cured under (a) *in-situ*, (b) adiabatic and (c) isothermal (50 °C) conditions. The strength estimates are compared to actual compressive strength values obtained from cubes cured in the laboratory replicating these curing conditions. The accuracy of these estimates for these curing regimes can now be examined.

5.3.1. In-situ temperature history of DTI blocks

The project carried out by the Concrete Society under a Partners in Technology Scheme, partly funded by the Department of Trade and Industry (DTI) – formerly the Department of Environment, Transport and the Regions (DETR), has provided the

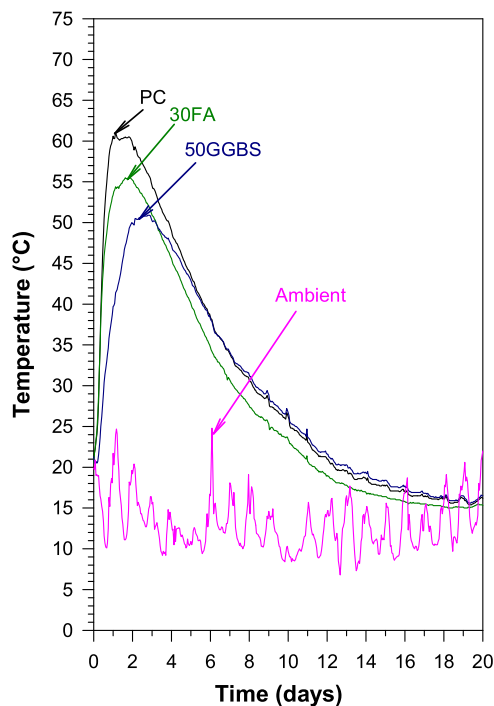


Fig. 9. In-situ temperatures recorded during summer for massive concrete blocks cast as part of the DTI project [56,57].

temperature histories shown in Fig. 9. It has become known as the “DTI project” and that is how it is referred to in this paper. The data generated has been very extensive and a big part of this has already been described in [57]. Only the temperature histories of concrete blocks, i.e. cubes with size of 1.5 m, are reported here. These blocks were insulated with 100 mm thick recycled expanded polystyrene sheets on all but one of the cube faces in order to simulate as much as possible mass concrete pours. The temperature histories of the summer concrete blocks have been selected for this study as it has been previously shown that the strength estimates of other structural elements were quite accurate [57] mainly because of the lower peak temperatures in these compared to blocks and also the shorter duration of temperatures above ambient. The combination of these two factors had only a very small effect on the early age (1–3 days) strength.

Peak temperatures in blocks cast during summer reached as high as 61 °C for the PC concrete. The heat dissipation during summer conditions was small and this helped increase the temperature inside the blocks. These must have accelerated the pozzolanic reaction, with 50GGBS and 30 FA mixes reaching temperatures of 51 °C and 56 °C, respectively. These are relatively small reductions in peak temperature from the 61 °C of PC; 10 °C and 5 °C lower for 50GGBS and 30 FA mixes, respectively.

The *in-situ* recorded temperature histories were simulated in the computer controlled temperature matched curing tank (TMC) shown in Fig. 2. Fig. 10 compares the experimentally determined TMC strength developments of cubes with those estimated by the maturity functions.

The Dutch weighted maturity method and the Nurse-Saul best estimate the 1-day strength of PC concrete, see Figs. 10(a) and 11(a). The Arrhenius function overestimates it as does the Weaver-Sadgrove method. The reason for the overestimate by the Arrhenius method could be the higher apparent activation energy previously determined for PC. The Rastrup function considerably overestimates the strength. All maturity functions overestimate the strengths beyond 1-day and the estimates deviate more from the actual TMC strengths with increasing age which confirms previous observations that maturity functions are valid until 72 h after casting [37,74]. This appears to be due to the inability of the maturity functions to account for the detrimental effect that high early age temperatures have on later age strength.

The Nurse-Saul function appears to underestimate the strength of the 50GGBS concrete at 1-day and also later ages, see Figs. 10(b) and 11(b). This is because this function assumes that the concrete or mortar strength gain rate varies linearly with temperature, irrespective of whether or not GGBS is used in the mix. GGBS has been shown to be more sensitive to temperature than PC, and this is also indicated by its higher apparent activation energy of 42.3 kJ/mol as compared with PC which is normally accepted to be around 30 kJ/mol (although it has been determined to be 41.2 kJ/mol using the TPE in this work). The significant strength improvement from the high *in-situ* temperatures for 50GGBS concrete are only expected to occur after 3-days, i.e. after the peak temperature of 51 °C has occurred and this was at 2.5 days. The Rastrup and the Dutch weighted maturity methods predict the strengths at 3-days relatively well. The predictions of the Arrhenius, Weaver-Sadgrove and Nurse-Saul underestimate the 3-day strength. All strength estimates converge to a single value at 42 days

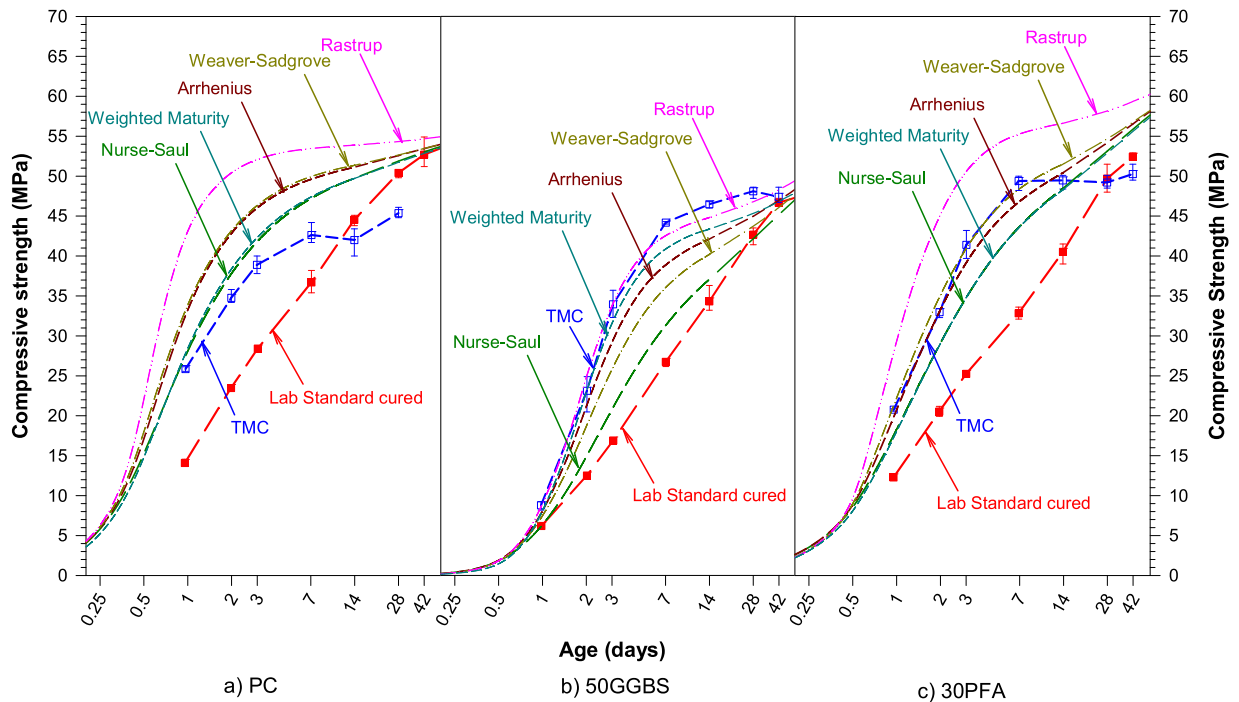


Fig. 10. Compressive strength estimates for summer blocks.

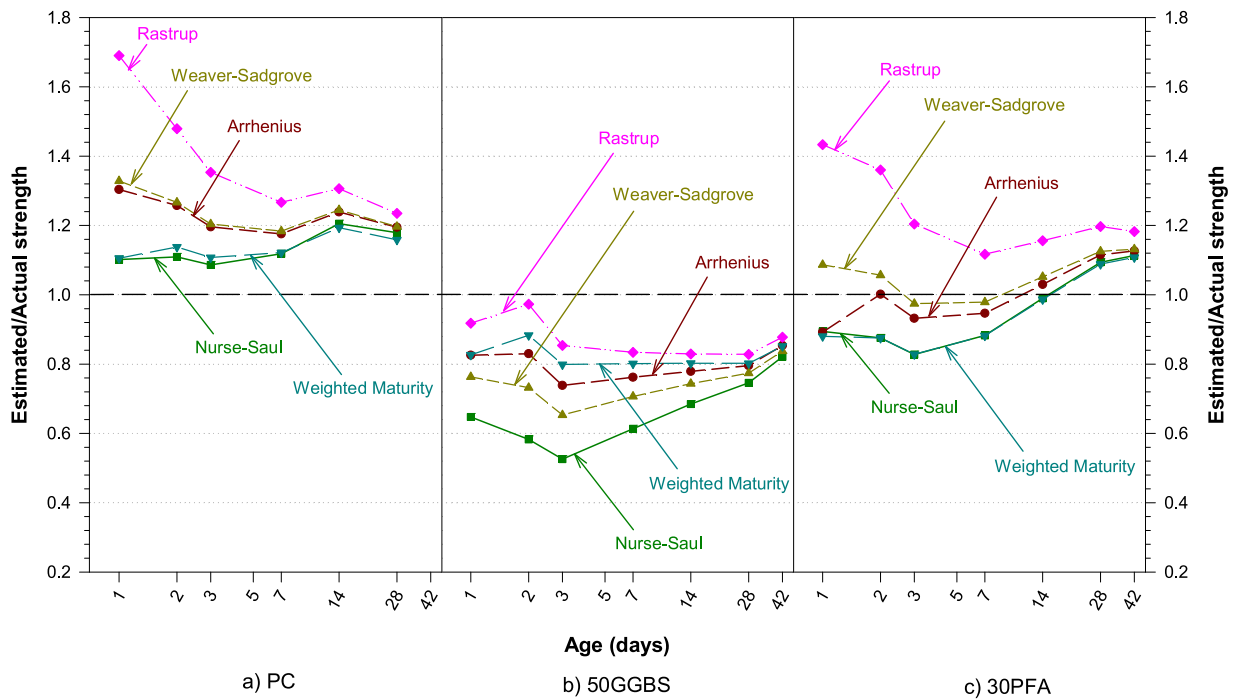


Fig. 11. Ratio of estimated/actual strengths for the DTI summer blocks.

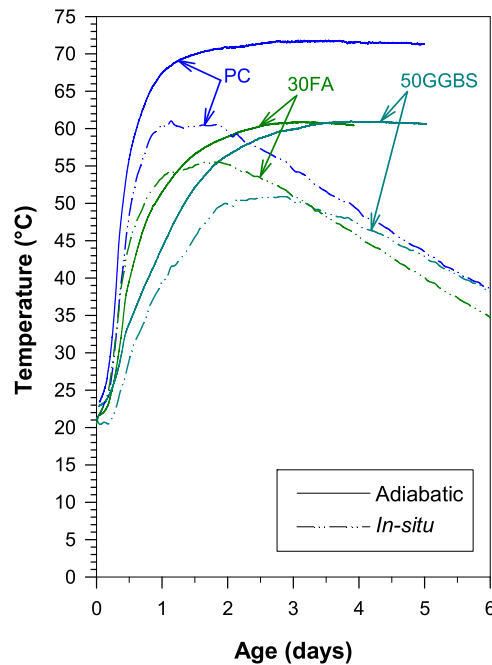


Fig. 12. Adiabatic and in-situ temperature histories of investigated concretes.

which was the latest testing age used for determining the strength-time relationship. There is no detrimental effect to the 42-day strength of 50GGBS concrete; the detrimental effect may be at a later age than this.

The peak temperature for the 30FA concrete mix occurs at 1.8 days and thus the strength improvements should be expected to be from 2 days onwards. The Arrhenius and Dutch weighted maturity methods estimate the strength improvement relatively accurately while the Nurse-Saul underestimates it and the Rastrup function overestimates it, see

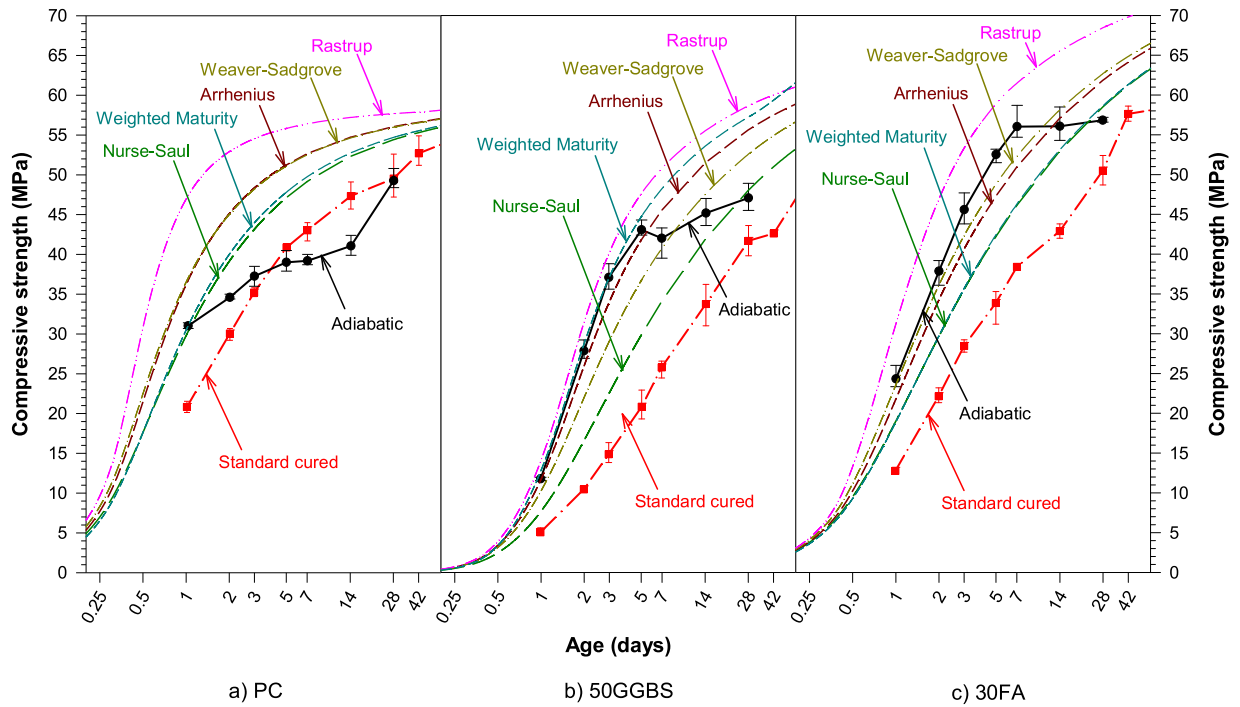


Fig. 13. Adiabatic compressive strength estimates.

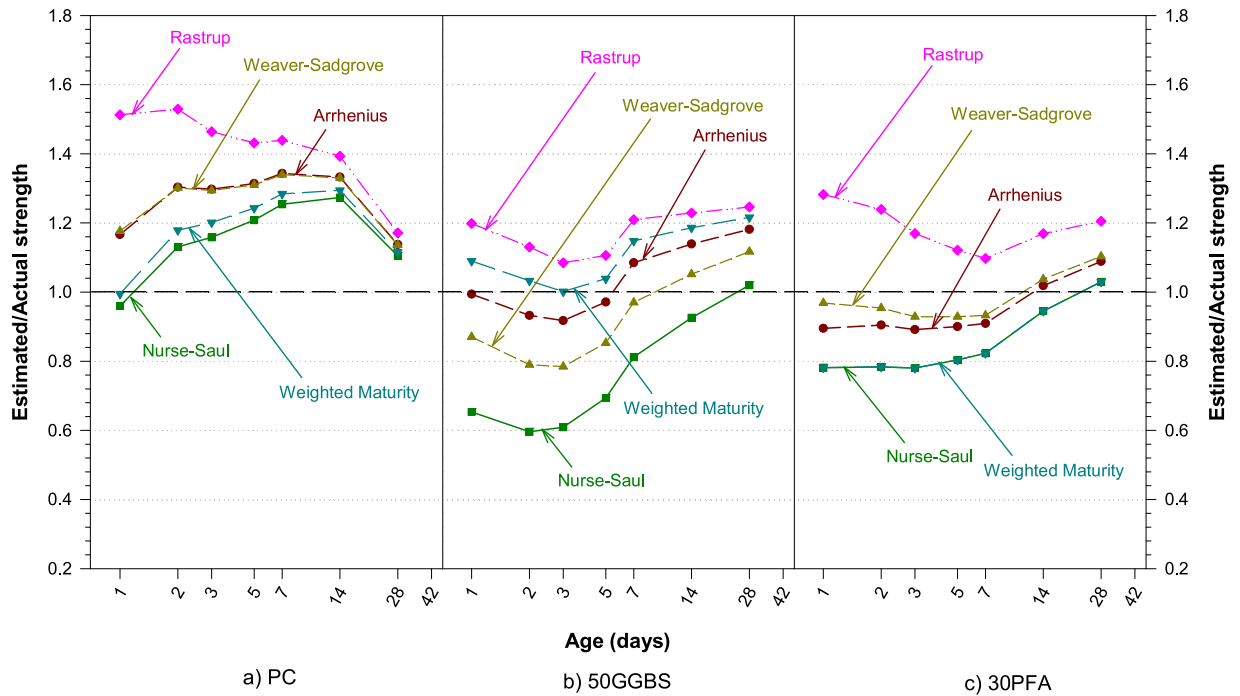


Fig. 14. Ratio of estimated/actual strengths for adiabatically cured specimens.

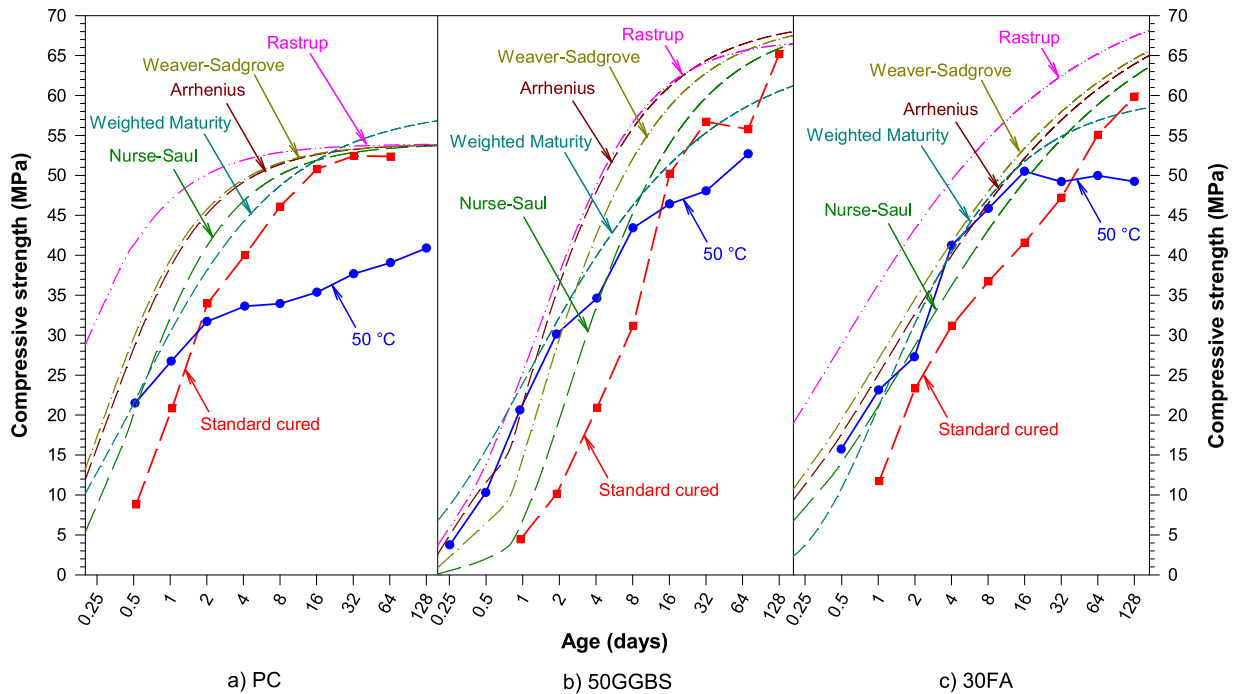


Fig. 15. Isothermally cured 50 °C compressive strength estimates.

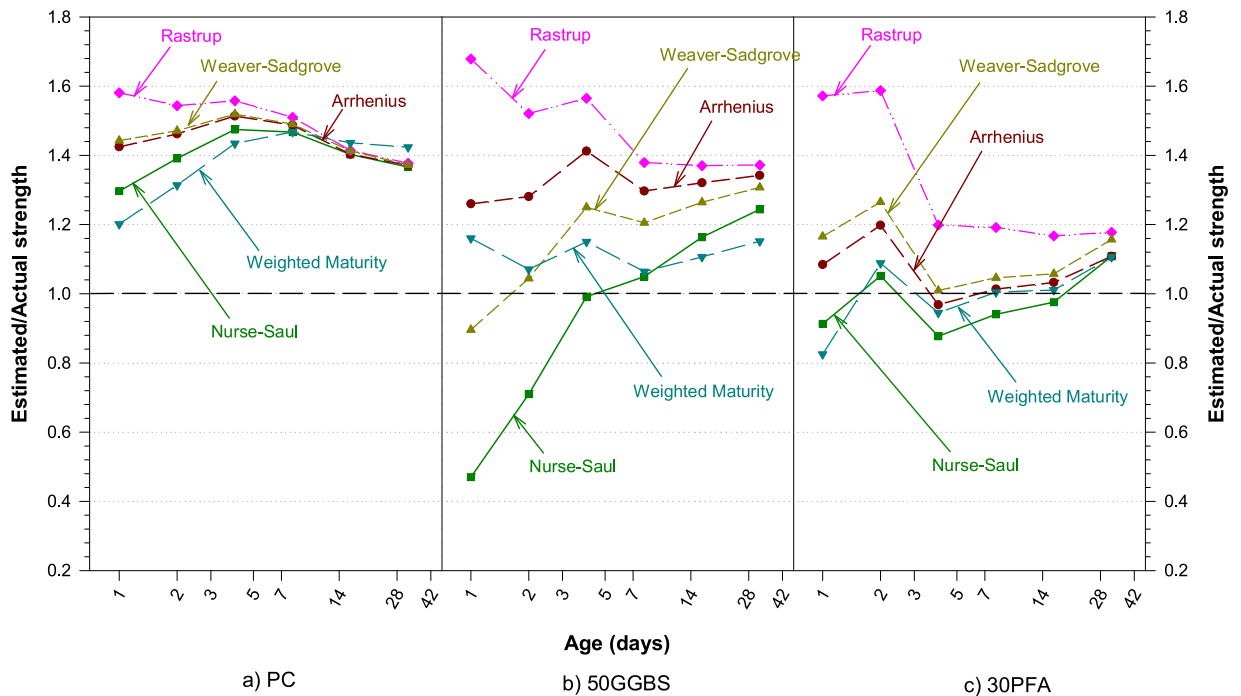


Fig. 16. Ratio of estimated/actual strength for 50 °C isothermally cured mortars.

Figs. 10(c) and 11(c). The estimated/actual strength ratios are plotted in Fig. 11 showing more clearly the above discussed trends.

5.3.2. Adiabatic strength estimates

The differences between the *in-situ* temperature histories and those obtained from adiabatic tests are that increases in temperature occur earlier and the peak temperatures are higher and they are maintained at this level for the duration of the tests, see Fig. 12. As such the trends in the strength estimates are similar, see Fig. 13, except that: (a) for the PC concrete, the strengths are overestimated more beyond 2-days, see Fig. 14(a), as the detrimental effect from the higher early age curing temperatures are increased, (b) the underestimation of strengths for the 50GGBS concrete are not only reduced but for some maturity methods like the Rastrup and Dutch weighted maturity methods they become overestimations, see Fig. 14(b); this again appears to be because of the detrimental effect higher early age curing temperatures have on long term strengths, and (c) for the 30 FA concretes the overestimates of the Rastrup function are slightly reduced, see Fig. 14(c).

5.3.3. Compressive strength estimates for isothermally cured 50 °C mortars

The difference between the two previous temperature histories, i.e. *in-situ* and adiabatic temperature histories, and isothermal curing is that the higher early age curing temperature is applied immediately after casting but this is lower at 50 °C from the peak temperatures shown in Fig. 12. The earlier application of the elevated curing temperature has the result that the “cross-over” effect appears earlier in all the three mortar mixes, i.e. at 2-days instead of beyond 3-days for the PC, 16-days instead of beyond 28-days for the 50GGBS and at 32-days instead of 42-days for the 30 FA concrete (Fig. 15, Fig. 16). There also appears to be a trend in the early age strength estimates, i.e. all the maturity functions overestimate the strength enhancements even at 1-day for PC whilst the underestimates for the 50GGBS and 30 FA are reduced (Fig. 16). This is believed to be an indication that the detrimental effect of high curing temperatures on strength is starting from very early age for isothermally cured mortars.

6. Conclusions

Strength estimates from the following maturity functions: Nurse-Saul, Rastrup, Weaver and Sadgrove, Freiesleben Hansen and Pedersen, and, the Dutch Weighted Maturity have been compared with actual strengths of concretes cured with temperature histories of *in-situ* blocks, adiabatic and isothermal 50 °C curing.

The main reason for the differences in strength estimates of the various maturity functions is the age conversion factor inherent/adopted in each. The Nurse-Saul, Weaver-Sadgrove and Rastrup functions are independent of the mix. It is only the Arrhenius and the Dutch weighted maturity methods that are mix specific. The former requires the determination of apparent activation energies whilst the latter requires the weighted factor C^n .

The linear relationship for the age conversion factor with temperature assumed by the Nurse-Saul function is quite different from the other maturity methods that have an exponential relationship. The linear relationship of the Nurse-Saul function is not only inadequate but it also does not differentiate the temperature sensitivities of the different cementitious systems, particularly for the GGBS mixes which have been shown to be more temperature sensitive.

High early age temperatures, such as those occurring in adiabatic or isothermal tests, appear to affect adversely the strength estimates and this is believed to be due to the detrimental effect of high curing temperatures on strength starting from a very early age.

None of the maturity functions accounts for the detrimental effect of high curing temperatures on later age strength and thus all of them overestimate the later age strengths. Consideration of this detrimental effect in the maturity functions will improve the strength estimates for both early and later ages.

Conflicts of interest

None.

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